Crack Growth Properties of FBR Structural Materials at Elevated Temperature

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ABSTRACT

In order to clarify the crack growth behavior of Fast Breeder Reactor (FBR) structural materials at operating temperature, crack growth tests of SUS304 stainless steel, 2.25Cr-1Mo steel and Mod.9Cr-1Mo steel were carried out under fatigue and creep condition at elevated temperature.

The fatigue and creep crack growth rates of them were successfully represented using cyclic J-integral range ΔJ and modified J-integral J', respectively. Meaningful difference of crack growth rates was not detected by each conditions, for example, between base metal and weld zone (weld metal and weld junction).

Two methods of the statistical analysis were studyed in order to evaluating scatter of the data. The one of them was the analysis assumed that the coefficients and exponents of the power low with ΔJ and J' obeyed simultaneous normal distribution. The other was the analysis weighted the lower crack growth rate data. These statistical analysis was carried out and relationship between variance and each parameters which were ΔJ and J' were obtained.

1 INTRODUCTION

In order to evaluate the structural safety of FBR,application of fracture mechanics has been studyed. The range of its application was used for the safety study of evaluation for leek before break (LBB). It has been used for the confidence study of the probability evaluation to estimate the life, recently. The confidence evaluation using fracture mechanics consists of three steps. They are crack initiation, crack growth and fracture. The purpose of this paper is to clarify the crack growth properties.

The crack growth tests of FBR structural materials were carried out at elevated temperature in PNC (Power Reactor and Nuclear Fuel Development Corp.). The data from 10^{-8} to 10^{-5} m/cycle under fatigue condition are necessary for the confidence evaluation. Under creep condition, the data from 10^{-9} to 10^{-7} m/hr are necessary, similarly.

The crack growth tests were carried out in whole crack growth rate region under fatigue conditions. But because limitation of time the creep crack growth tests could not be carried out under the crack growth conditions of less than 10^{-7} m/hr Then it is necessary to extrapolate the data of lower crack growth rate region. Usual extrapolation was used to extend averaged trend line of data. It could be risky estimation. Then the evaluation of the crack growth properties which considered scatter of the data is necessary in order to elevate the confidence of the extrapolation.

In this paper, the results of crack growth tests of SUS304 stainless steel, 2.25Cr-1Mo steel and Mod.9Cr-1Mo steel, which are structural materials of FBR under fatigue and creep conditions at elevated temperature are shown. Further the results of the statistical analysis for these crack growth data are shown.

2 TESTS AND RESULTS

Table 1 shows conditions of fatigue and creep crack growth tests. Materials are both base metal and weld zone of SUS304 stainless steel, Mod.9Cr-1Mo steel, 2.25Cr-1Mo steel. Base metal were distinguish between rolled plates and forged materials. Materials treated G.E. step cooling and damaged by creep or fatigue tests were used, further. Testing temperature is from 450°C to 650°C. Testing method is the standard method determined by 17 research institutes of Japan under the sponsorship of PNC. (Y.Asada et al.1989) ΔJ and J' were selected for the parameters for fatigue and creep crack growth properties.

Table 1 Conditions of crack growth tests

Materials		Temperature (°C)	Base metal	Weld metal	Weld junction	HAZ	HAZ Soft	G.E.step cooling	Creep damage	Fatigue damage
SUS304	Rolled plate	550	13,6*	1,1*	1,1*					
		650	14,6*							
	Forged material	450	3							
		550	3							
		650	2							
2.25Cr-1Mo	Rolled plate	500	5,2*	1,1*	1,2*	1,2*		1	2	2*
		550	1,3*							
Mod.9Cr-1Mo	Rolled plate	500	2,3*	1,2*	1,2*	1,2*	1			
		600	1,3*	2*						
	Forged material	500	2							
		550	2*	2*		2*				
		600	2							

Fatigue crack growth tests
*Creep crack growth tests

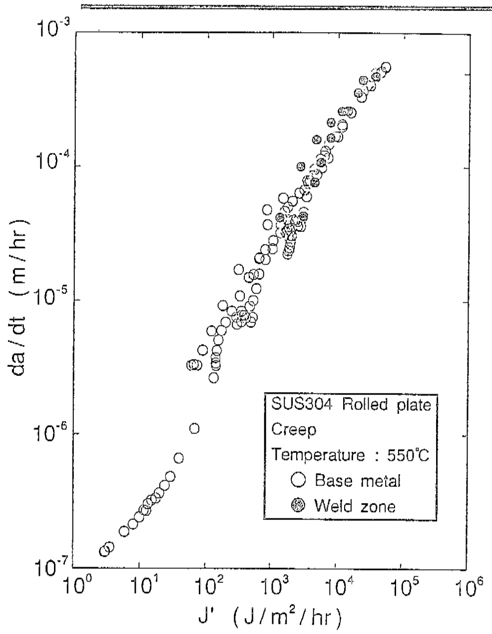

Fig.1 Relationship between J' and da/dt of SUS304

Figure 1 shows result of creep crack growth test of SUS304 stainless steel at 550°C. Meaningful difference was not detected between base metal and weld zone. It was not detected by the difference of specimen shape and temperature, too. It was same in other materials.

3 CRACK GROWTH ANALYSIS USING STATISTICAL ANALYSIS

The results of analysis of the relationship between stress intensity factor range and fatigue crack growth rate using statistical analysis were reported (J.Kwon et al. 1987; T.Sakai et al. 1979).In this paper it is reported that result of analysis of creep crack growth data of SUS304 stainless steel using their methods. Because meaningful deference of the relationship J' and da/dt was not detected by the test condition, all data were treated in one series.

In first step, the crack growth data of one spacemen were arranged in order da/dt. w_j which was a weight parameter of No.j's data was defined as equation 1. Using of the method of least squares, the relation was proposed on basis of power low showed by equation 2. Coefficient is C, exponent is m. The average of S_t which were variances of each specimens, was defined as $\overline{S_t}$.

$$w_j = \log\left(\frac{da}{dt}\right)_{j+1} - \log\left(\frac{da}{dt}\right)_{j-1} \tag{1}$$

$$\frac{da}{dt} = C(J')^m \tag{2}$$

Generally, it is said that logC and m obey normal distribution [2]. Assuming that logC and m obey simultaneous normal distribution, when weight parameter of No.i's specimen data was defined as W_i and average and variance of logC and m were defined $\overline{X}_c$, $\overline{X}_m$, S_c^2, S_m^2, averaged trend line,$\overline{X}$ and variance,S^2 of creep crack growth rate are expressed by equation 4 and 5, severally.

$$W_i = \left\{ \log\left(\frac{da}{dt}\right)_{max} - \log\left(\frac{da}{dt}\right)_{min} \right\}_i \tag{3}$$

$$\overline{X} = \overline{X}_c + \overline{X}_m \log J' \tag{4}$$

$$S^2 = S_c^2 + 2\gamma S_c S_m \log J' + (S_m \log J')^2 + \overline{S_t}^2 \tag{5}$$

Variance has been expressed easily assuming that m was constant,logC obeied m (γ=0), or there was not correlation between logC and m [3]. In this paper, using γ which was obtained from tests, variance was calculated by equation 5. Fatigue and creep crack growth rates of all materials are calculated by same method.

Figure 2 shows averaged trend line and 95% confidence interval of creep crack growth rate of SUS304 stainless steel. Open marks are all experimental data.Almost data are installed in confidence interval. and so this interval represents scatter of J'-da/dt relation.

Figure 3 shows 95% confidence interval of creep crack growth rates of SUS304 stainless steel,2.25Cr-1Mo steel and Mod.9Cr-1Mo steel. The order of creep crack growth rates is SUS304 > 2.25Cr-1Mo > Mod.9Cr-1Mo. Similarly, figure 4 shows 95% confidence interval of fatigue crack growth rates of SUS304 stainless steel,2.25Cr-1Mo steel and Mod.9Cr-1Mo steel. The order of fatigue crack growth rates is 2.25Cr-1Mo > SUS304 > Mod.9Cr-1Mo. But difference of width of confidence interval in materials are detected clearly.

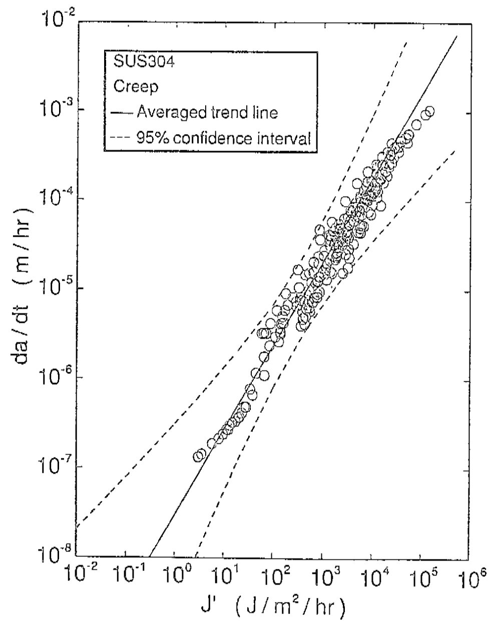

Fig.2 95% confidence interval and averaged trend line of creep crack growth rate of SUS304

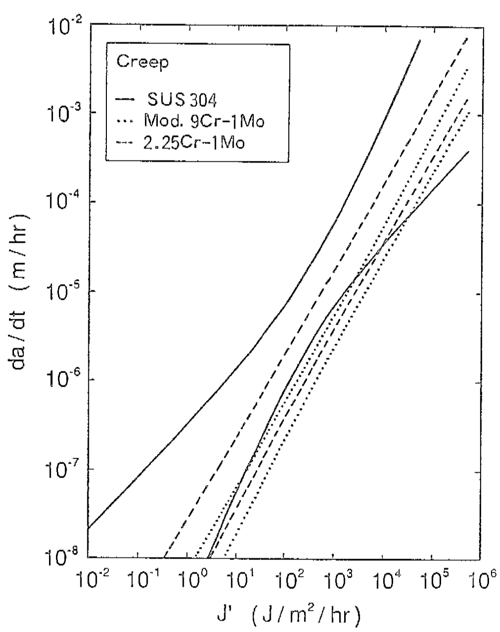

Fig.3 95% confidence interval and averaged trend line of creep crack growth rate of SUS304, 2.25Cr-1Mo and Mod.9Cr-1Mo

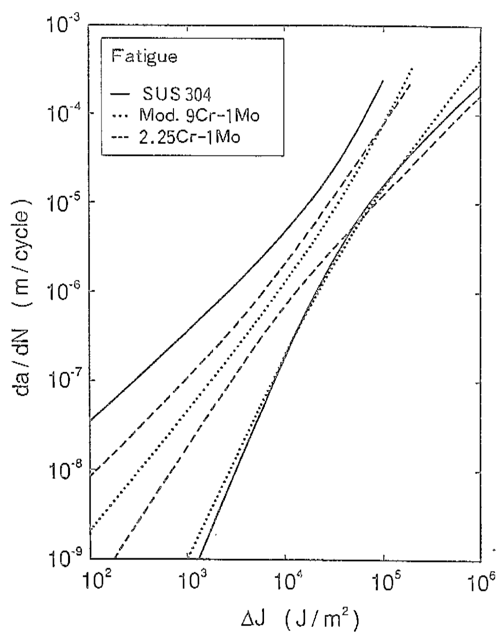

Fig. 4 95% confidence interval and averaged trend line of fatigue crack growth rate of SUS304, 2.25Cr-1Mo and Mod.9Cr-1Mo

In this method lower crack growth rate region data and higher crack growth rate region data give same evaluations, if logC and m are same values. Because there are few lower rate region data, these data could not have a effect on evaluation. It is so difficult to obtain lower rate region data, that it is necessary to extrapolate to lower rate data. Therefore the evaluation considerated weight of lower rate data is necessary, in order to elevate confidence of extrapolation. Secondly it was carried out in trial that was the evaluation considerated weight of lower rate region data.

4 Evaluation considerated low crack growth rate data

There is one of the extrapolations for creep rapture life which considerates scatter from difference of heat conditions and spends few data usefully. (K.Iida et al. 1978) Using this method, the evaluation considerated low crack growth rate data was carried out.

On behalf of the data from No.i's specimen, relationship between logJ' and da/dt was expressed in the median point (x_i, y_i). The regression equation is expressed by equation 6. Where $\bar{x}$ and $\bar{y}$ express mean of x_i and y_i, each other.

$$y - \bar{y} = b(x - \bar{x}) \tag{6}$$

$$b = \frac{\sum (x_i - \bar{x}) y_i}{\sum (x_i - \bar{x})^2} = \sum a_i y_i \tag{7}$$

$$a_i = \frac{(x_i - \bar{x})}{\sum (x_i - \bar{x})^2} \tag{8}$$

$S^2_{(y_i)}$ and $S^2_{(b)}$ which are variances of y_i and b, are expressed by each equation 9 and equation 10.

$$S^2_{(y_i)} = \frac{\sum \{y_i - \bar{y} - b(x_i - \bar{x})\}^2}{(n - 2)} \tag{9}$$

$$S^2_{(b)} = \sum a_i^2 S^2_{(y_i)} = \frac{S^2_{(y_i)}}{\sum (x_i - \bar{x})^2} \tag{10}$$

Equation 11 shows $\hat{y}$ which was averaged trend line and equation 13 shows S^2 which was variance of prediction value of y. In the right side of equation 13, the first term results from scatter of y_i, second term results from $(\bar{x}, \bar{y})$ and third term results from b. The prediction interval is expressed using t-distribution. Where degree of freedom is equal to n-2.

$$\hat{y} = \bar{y} + b(x - \bar{x}) \tag{11}$$

$$S^2_{(\hat{y})} = S^2_{(\bar{y})} + (x - \bar{x})^2 S^2_{(b)} = S^2_{(\frac{1}{n}\sum y_i)} + (x - \bar{x})^2 S^2_{(b)} = S^2_{(y_i)}\left(\frac{1}{n} + \frac{(x - \bar{x})^2}{\sum (x_i - \bar{x})^2}\right) \tag{12}$$

$$S^2 = S^2_{(\hat{y})} + S^2_{(y_i)} = S^2_{(y_i)}\left(1 + \frac{1}{n} + \frac{(x - \bar{x})^2}{\sum (x_i - \bar{x})^2}\right) \tag{13}$$

Figure 5 shows 95% prediction interval obtained from this method by solid lines and 95% confidence interval obtained from the method explained on paragraph 3 by broken lines for creep crack growth data of SUS304. Almost crack growth data are installed in the prediction interval. Prediction interval evaluates scatter of data vary well. This prediction interval is narrower than confidence interval on lower crack growth rate region. This prediction interval evaluates scatter of data,which has weighted lower crack growth rate region data.rationally.

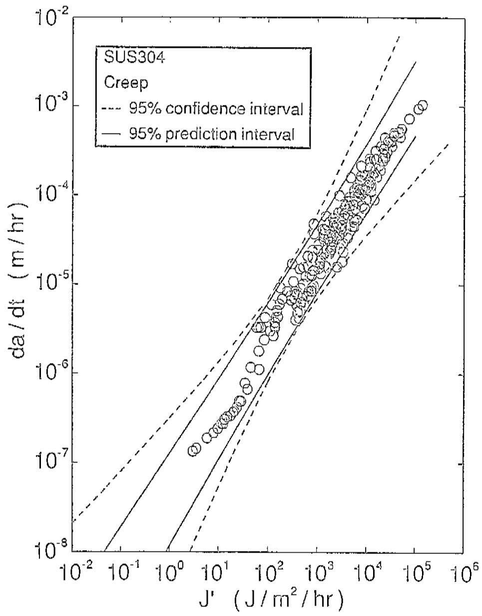

Fig.5 95% prediction interval and 95% confidence interval of creep crack growth rate of SUS304

5 CONCLUSION

Crack growth tests of SUS304 stainless steel, 2.25Cr-1Mo steel and Mod.9Cr-1Mo steel under fatigue and creep conditions at elevated temperature were carries out. Statistical analysis for the relationship between crack growth rates and each parameter, ΔJ and J' was carried out,further.

Meaningful difference of ΔJ-da/dN and J'-da/dt relation were not detected in any conditions which were difference between base metal and weld zone and difference of temperature, for example.

95% confidence intervals were expressed. They estimated scatter of the crack growth data well. The order of the creep crack growth rates was SUS304 > 2.25Cr-1Mo > Mod.9Cr-1Mo . The order of the fatigue crack growth rates was 2.25Cr-1Mo > SUS304 > Mod.9Cr-1Mo.

Further,the prediction intervals were expressed using one of the extrapolations for creep rapture life which considerates scatter cause of difference of heat conditions. The few lower crack growth rate data could be considered in this evaluation, rationally.

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